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WALL TURBULENCE CONTROL

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Abstract

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A variety of wall turbulence control devices which have been experimentally investigated are discussed; these include devices for burst control, alteration of outer flow structures, large eddy substitution, increased heat transfer efficiency and reduction of wall pressure fluctuation intensity.

Control of pre-burst flow has been demonstrated with a single, traveling surface depression which is phase-locked to elements of the burst production process. It was shown that the near-wall streamwise flow could be accelerated and thereby reduce the tendency of a retarded streamwise velocity profile to inflectionally break down (burst).

Another approach to wall turbulence control is to interfere with outer layer "coherent structures." Studies have shown that a cylinder adjacent to a flat plate produces a modified Karman vortex street. If the cylinder is sufficiently close to the plate, one component of shed vorticity will be suppressed altogether. Such a device in the outer part of a boundary layer was shown to suppress turbulence and reduce drag by opposing both the mean and unsteady vorticity in the boundary layer.

Large eddy substitution is a method in which streamline curvature (known to suppress turbulence) is introduced into the boundary layer in the form of streamwise vortices. Several systems of streamwise vortices were generated in a turbulent boundary layer. It was shown that boundary layer entrainment rates were reduced below normal flat plate values and indicated the successful suppression of turbulence.

Riblets, which have already been shown to reduce turbulent drag, have also been shown to exhibit superior heat transfer characteristics. Heat transfer efficiency as measured by the Reynolds Analogy Factor was shown to be as much as 36 percent greater than a smooth flat plate in a turbulent boundary layer.

Large Eddy Break-Up devices (LEBU) which are also known to reduce turbulent drag have been shown to reduce turbulent wall pressure fluctuation.

Wall Turbulence Control

Research conducted by the Viscous Flow Branch/High-Speed Aerodynamics Division has shown that it is now possible to reduce or enhance a number of turbulent boundary layer flow properties. This presentation will review our progress in the wall turbulence control area starting with new uses for existing turbulence control devices and following with a variety of new concepts aimed primarily at turbulent, viscous drag reduction. New uses for existing devices include riblets used as high-efficiency heat transfer surfaces and LEBU's (large eddy break-up device) used to control wall pressure fluctuations. New concepts for drag reduction include Large Eddy Substitution which shows that the favorable influence of wall curvature on turbulence may also be obtained with streamline curvature on a flat plate; Opposing Unsteady Vorticity which shows the feasibility of altering large-scale structures in the boundary layer by introducing opposite sense vortices; and Active Phase-Locked Wall Deformation which shows the possibility of controlling turbulent wall bursting through flow-triggered, electromagnetically actuated wall motion.

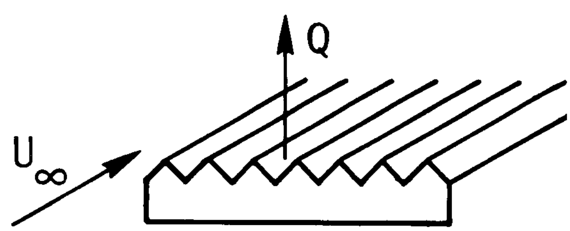
- Reduce or enhance properties of turbulent wall boundary layers (drag, heat transfer, noise, etc.)
- New uses of existing devices
  - Riblet: efficient heat transfer surface
  - LEBU: reduces wall pressure (density) fluctuations
- New concepts for drag reduction
  - Large eddy substitution
  - Opposing unsteady vorticity
  - Active phase-locked wall deformation

Heat Transfer Efficiency of Riblet Drag Reducing Surfaces

In addition to the drag reducing property of a riblet surface, it also allows for greater heat transfer efficiency than a smooth or rough surface. This finding is based on low-speed heat transfer and drag measurements on a flat, heated riblet model. Heat transfer efficiency is defined by the Reynolds analogy factor. Potential application for this finding is in the field heat exchanger design where an increase in the Reynolds analogy factor allows for multiparameter optimization studies (heat transfer, pumping power, size, weight, etc.).

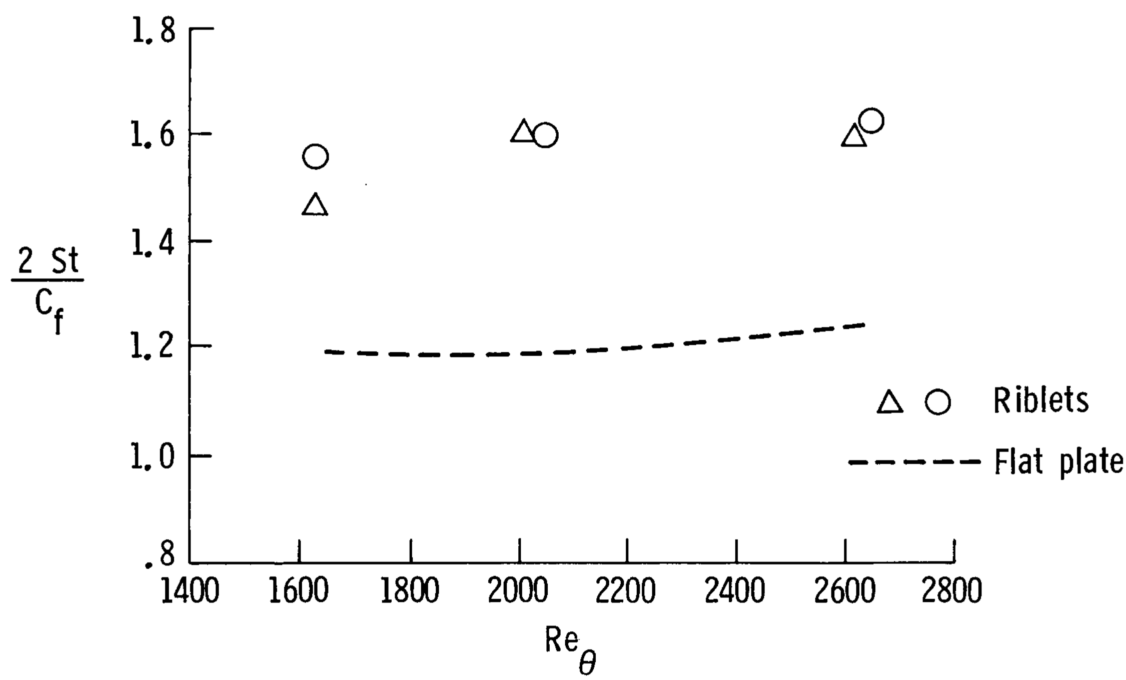
- Riblets show higher heat transfer efficiency than smooth or rough surfaces
- Efficiency determined by experimentally measuring Reynolds Analogy factor

  ($2\ St/C_f$ St = Stanton #, C_f = skin friction coefficient)
- Application to heat exchanger optimization/efficiency



Reynolds Analogy Factor for Riblets

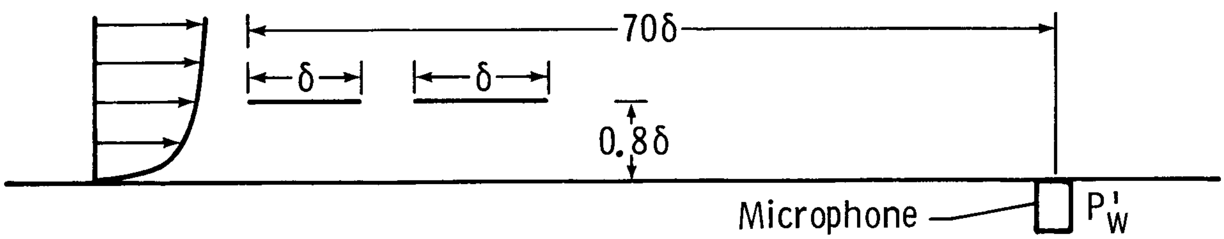
This plot shows the results of measurement of the Reynolds analogy factor for the riblet heat transfer model as well as a reference smooth flat plate. The ordinate is the Reynolds analogy factor (the ratio of two times the Stanton number to the skin friction coefficient). The abscissa is the Reynolds number based on the stream velocity and momentum thickness. As can be seen, the flat plate data remain roughly constant at approximately 1.2 which is the usually quoted value for a flat plate in air. Two types of riblet surfaces, both exhibiting drag reduction, were tested and have Reynolds analogy factors 30 percent higher than the smooth flat plate.



Effect of LEBU on Wall Pressure Spectra

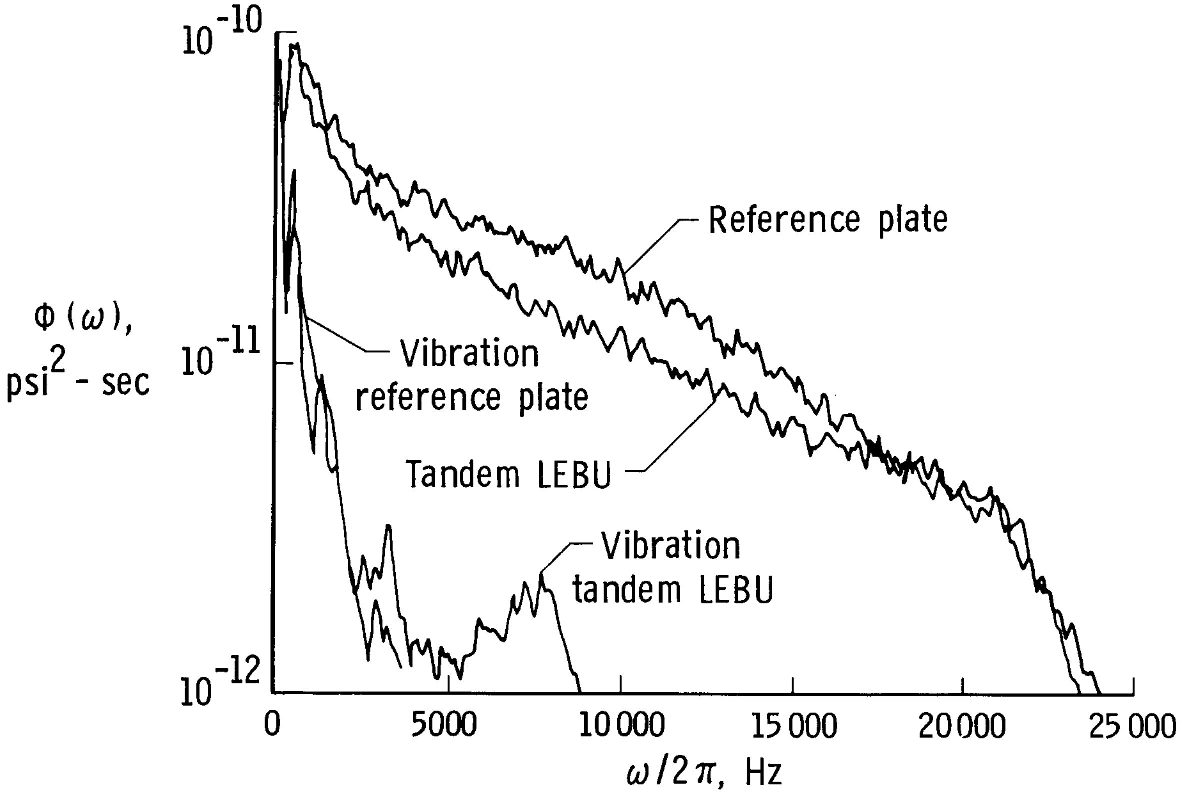
LEBU's affect turbulent, viscous drag apparently by their effect on the large-scale structures in the outer part of the boundary layer. Since these same large-scale structures are responsible for a significant portion of indicated wall pressure fluctuation intensity, reduction in the large scales should cause a similar reduction in wall pressure intensity. To test this hypothesis, a pinhole microphone was used to measure wall pressure spectra downstream of a tandem LEBU at the streamwise location of maximum skin friction reduction. It was found that in the frequency range of the large eddies, the fluctuation intensity was reduced by 25 percent below the reference smooth flat plate level. This finding has potential application to boundary layer noise reduction on aircraft allowing for reduced weight of sound insulation. Density fluctuation intensity should also be reduced to allow for improved performance of aircraft radar domes and laser or IR windows.

- Expect change in wall pressure due to breakup of large scale structures
- Measured wall pressure $\left(P_W'\right)$ spectra downstream of LEBU
- P_W' reduced $0(25\%)$
- Applications: Reduced self noise on sonar domes
  Improved laser and IR window performance
  Reduced weight of sound insulation on aircraft



Wall Pressure Spectra Downstream from LEBU

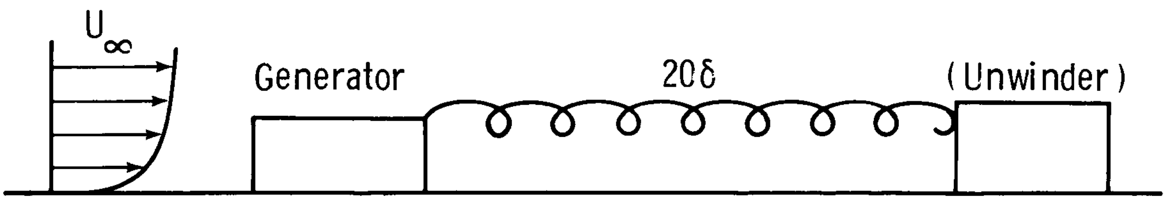
This plot shows the results of the LEBU wall pressure spectral measurements. The ordinate is the mean-square spectral intensity; the abscissa is frequency. For data above 2000 Hz and less than 15000 Hz, there is a clear drop in mean-square spectral intensity. Above 15000 Hz, the LEBU data rejoin the reference flat plate data indicating that the LEBU is affecting the large-scale structures. Since the diaphragm-type microphone beneath the pinhole was sensitive to structural vibrations, the indicated pressure spectra (actually due to vibration) were determined by covering the pinhole during a run. Results shown in the figure indicate that the data below 2000 Hz are excessively distorted by structural vibration and are not correct.



Large-Eddy Substitution via Vortex Cancellation

The large-eddy substitution concept is an extension of turbulence suppression by convex wall curvature. By introducing streamline curvature (as opposed to wall curvature) into turbulent wall flows via co-rotating streamwise vortices, similar turbulence suppression may be possible. The idea is to "wrap-up" and suppress the turbulence in vortex-induced curvature over a streamwise processing region and then remove the vortices. Two techniques were studied: vortex cancellation and vortex self-annihilation. Vortex cancellation employs widely spaced rectangular strakes to generate a spanwise array of co-rotating wall vortices. Opposite sign generators (i.e., unwinders) are placed 20 boundary layer thicknesses downstream to remove the vortices. Vortex self-annihilation employs closely spaced generators which produce vortices which self-destruct downstream of the generators. To determine the effectiveness of the devices, boundary layer growth was measured to estimate the rate at which free-stream air was entrained by the turbulence into the boundary layer. Lower entrainment rates indicate suppression of turbulence. In each case, the entrainment rate was reduced below flat-plate reference levels. Details of this work are presented in Reference 1.

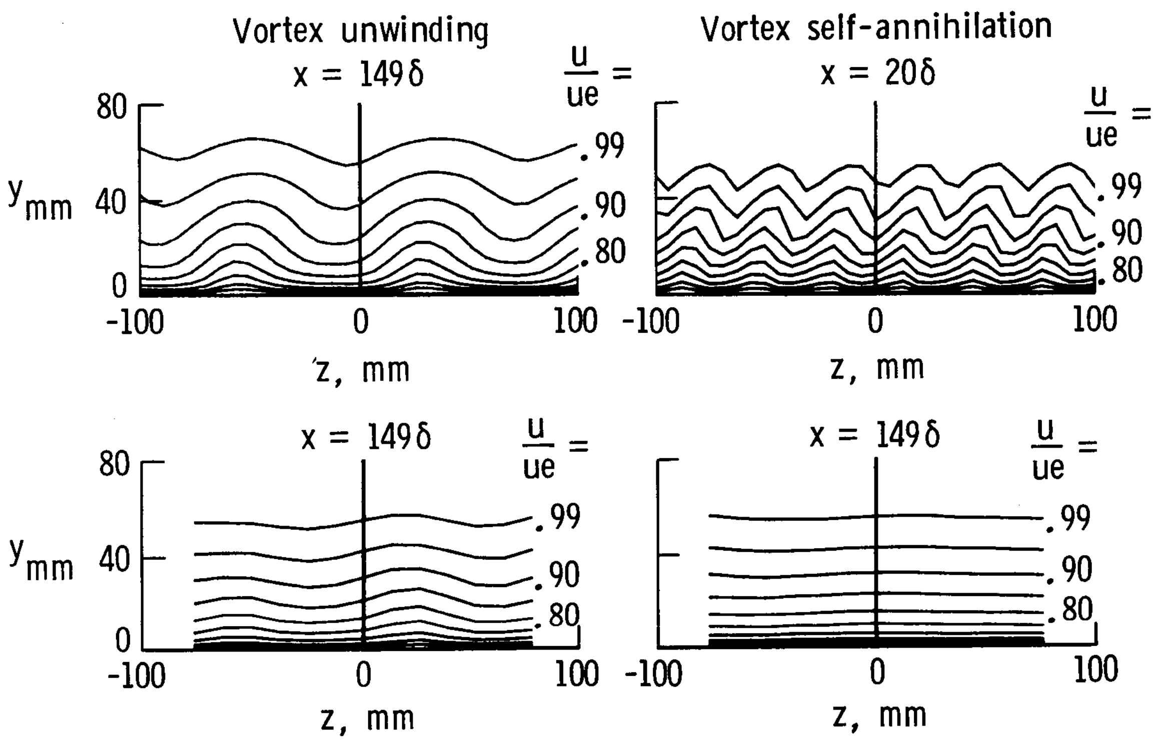
- Co-rotating, longitudinal vortices used to study effect of streamline curvature (induced by vortex) on turbulent wall flow
- "Wrap-up" turbulence in curvature substituting vortex for turbulence
- Two methods employed:
  - Widely spaced generators with unwinders (cancellation)
  - Closely spaced generators without unwinders (self-annihilation)
- Boundary layer entrainment decreased in both cases



Large-Eddy Substitution

This figure shows the effect of the two techniques of creating and eliminating wall vortices. The left-hand figures demonstrate vortex cancellation. The top figure shows spanwise contours of constant velocity 149 boundary layer thicknesses downstream of the vortex generators without vortex unwinders. The bottom figure shows the same streamwise location with vortex unwinders located 20 boundary layer thicknesses downstream of the generators. As can be seen, the unwinders are very effective in removing the vortices.

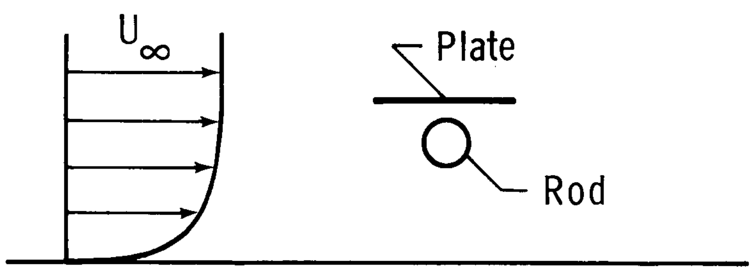
The right-hand figures demonstrate the vortex self-annihilation concept. The top figure shows the generated vortices 20 boundary layer thicknesses downstream of the generators. The bottom figure shows the absence of vortices 149 boundary layer thicknesses downstream of the generators due to the self-annihilation process.



Effect of Opposing Unsteady Vorticity on Turbulent Structures in Wall Flows

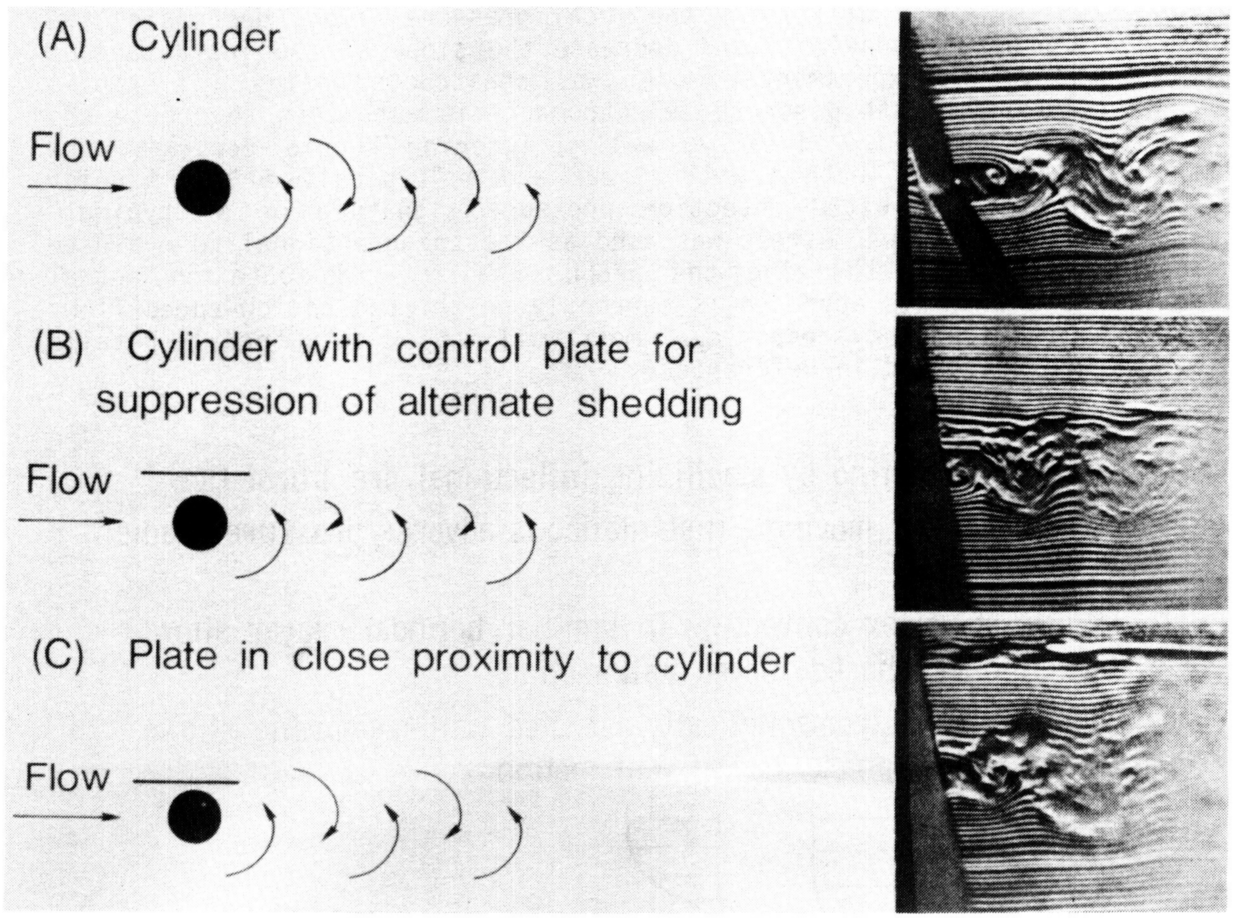
Coherent structures in the outer part of a wall boundary layer have fluctuating vorticity of the same sign as that of the mean boundary layer. A possible technique for controlling these structures is to introduce vorticity of the opposite sign to counteract the existing coherent structures. A two-dimensional rod in a flow normally produces an alternating vortex pattern downstream of the rod (Karman vortex street). By placing a thin control plate at a proper distance from the rod, one side of the vortex street will be reduced. This method may be used to introduce the vortices required to counteract the coherent structures in the outer part of the boundary layer. Total drag reduction on the order of 25 percent was measured with this technique of which 20 percent was due to the momentum deficit introduced by the device and an additional 5 percent presumably due to turbulence modification by the device. Details of this work are presented in Reference 2.

- Counteract outer layer "coherent structures" by introducing vorticity of opposite sign
- Use Karman vortex street from 2-D rod with one side of street suppressed by control plate
- Viscous drag reduced 0(25%): 20% momentum deficit
  5% turbulence modification



Production of Control Vortices for Turbulence Modification

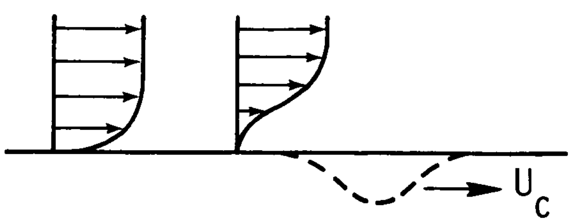
This figure shows the effect of the vortex street control plate for a rod in a uniform flow. The arrangement of the device is shown schematically on the left with smoke-wire flow visualization of the downstream vortices on the right. Part A shows the unaltered Karman vortex street. Part B shows the effect of optimum placement of the control plate. Note the reduction in strength of the upper part of the vortex street. Part C shows the effect of placing the control plate too close to the rod. In this case, the rod and control plate act as a single obstacle to the flow.



Turbulent Burst Control Through Phase-Locked Wall Deformation

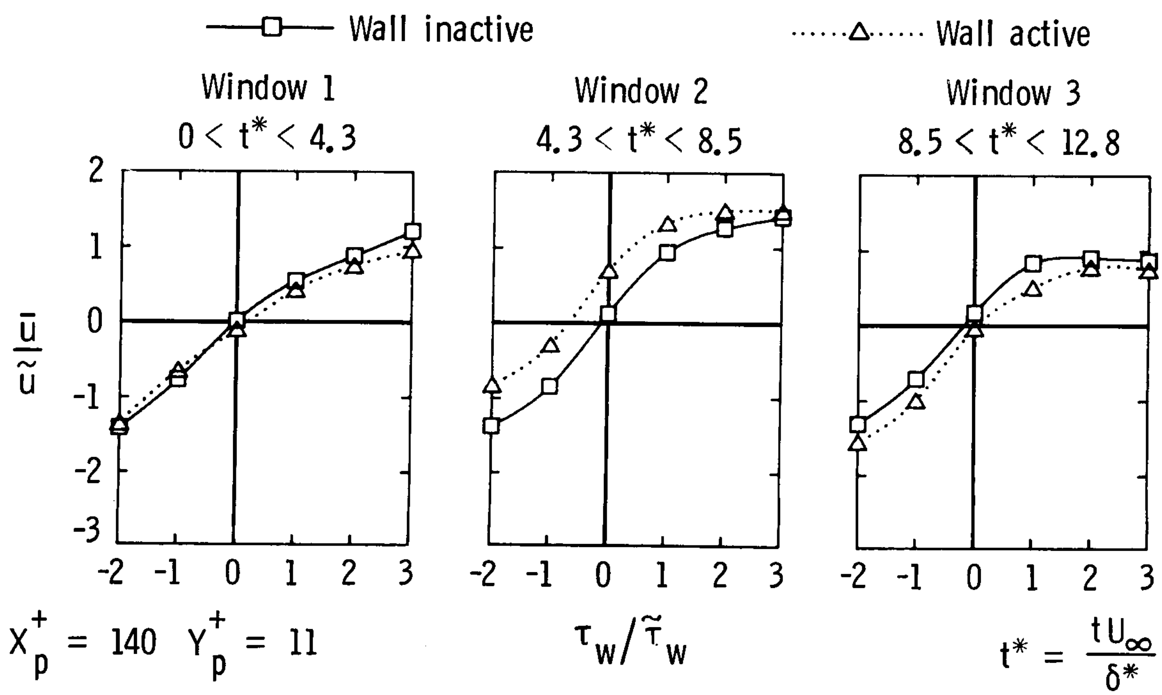
Data on coherent structures close to the wall suggest the possibility of controlled wall motion as a means of altering the bursting process. An inflectional instability model of the bursting process was used as a basis for design of the control mechanism. Briefly, the flow model states that low-speed wall streaks and "typical" eddies play a synergistic role in burst production. Wall streaks start the inflection of an initially quiescent, preburst streamwise velocity profile near the wall and the moving, adverse pressure gradient associated with the "typical" eddy adds to the inflection causing turbulent breakdown (bursting). Calculations have shown that a traveling wall depression phase-locked on the low-pressure region beneath a convecting "typical" eddy will raise the local pressure (i.e., decreasing the moving adverse pressure gradient) and decrease the slope of the instantaneous velocity profile. An experimental model was constructed using a flexible, ferromagnetic membrane with discrete, electromagnetic actuators to create the traveling wall depression. Ideally, wall triggering should occur at the simultaneous detection of both a wall streak and a "typical" eddy. A noisy tunnel environment prohibited detection pressure signature of a "typical" eddy. Therefore, wall shear stress was used as the trigger signal to evaluate the effectiveness in stabilizing the preburst flow. No data on actual bursting was taken. (This approach is currently restricted to low-speed flows due to the limited frequency response of most wall motion actuators.) Details of this work are presented in Reference 3.

- Stop turbulent bursting by stabilizing inflectional pre-burst flow
- Based on cancelling moving, instantaneous adverse pressure gradient due to typical eddy
- Calculations of vortex convecting in laminar boundary layer show favorable effect of phased-locked wall motion
- Experiment with electromagnetically actuated wall membrane shows stabilizing effect of phase-locked wall motion



Streamwise Velocity Fluctuation Component for Phase-Locked Wall

In order to determine whether the traveling wall depression model could stabilize preburst flow, wall motion was triggered on various levels of wall shear-stress measured at a point just upstream of the wall device. A depression convection speed of 0.75U was used. Hot-wire anemometry was used to measure turbulent velocity fluctuations above the first actuator in the wall device. These data were then ensemble averaged over three short time intervals for 250 cycles of wall motion. The time intervals or windows were chosen to bracket the time during which the wall was depressed immediately beneath the hot-wire probe. The figure shows the normalized, ensemble-averaged, streamwise velocity fluctuation component for the three time windows both with and without wall motion. It is evident in window 2 that the effect of the wall motion is to accelerate the streamwise flow near the wall. The first window shows no significant effect of secondary, propagating wall waves (caused by the impulsively started wall motion) which travel faster than the wall depression. The third window shows that wall continued to oscillate after the wall depression passed. The primary finding, however, is that the traveling wall depression can stabilize preburst flow.



CONCLUSION

We have shown in these initial experiments that wall turbulence can be reduced or amplified by a variety of techniques including embedded bodies, non-planar wall geometries and phase-locked control. The payoff of such control includes drag reduction, reduced sound insulation, increased heat exchanger efficiency, improved performances of laser and IR windows and reduced self noise on sonar domes.

References

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